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AN ENERGY APPROACH TO THE FATIGUE LIFE OF SHIP PROPULSION SYSTEMS

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Abstract. The conducted research investigations aimed to carry out an identification of the constructional materials fatigue state of the ship propulsions' rotational mechanical units for diagnostic purposes. The fatigue cracks of the elements transmitting mechanical energy streams from the propulsion engines to the ship propellers or to the generators of the ship's electric power station stand for a primary reason for the secondary, usually very extensive, damages within the ship's main or auxiliary propulsion system. It inevitably leads to immobilizing the ship along with further consequences for her stability and unsinkability. The shafts line's misalignment or bend represent the most frequent reasons of this kind damages. They usually occur as a consequence of the foundations' static settlement of the shafts line's main components, alternatively, as a consequence of the ship's slight but frequent collisions during her handling in harbors.

A laboratory test bed of the simple rotational mechanical unit driven by the electric engine has been especially designed and built for a purpose of the research program realization. It stands for, in a smaller scale, a physical model of the real object what makes possible an actual introducing the external inputs which are characteristic to the propulsion shafts line's misalignment. The test bed was equipped with a measuring set enabling a registration of the course of the multisymptomatic, continuous and irreversible alterations of the shaft section's fatigue state while it is subject to cyclic torsional-bending loads during the standard fatigue test. The measuring system makes possible a simultaneous observation of the parameters characterizing accumulation and dissipation processes of different energy forms in the slow-changeable, dynamic process of the fatigue test.

A patent application regarding the solution related to energy symptoms measurements of the constructional materials' high-cycle (mechanical) fatigue presented in the paper has been protected by the Patent Office of the Republic of Poland, as a utility pattern, the registration number: 67362 - "Laboratory test bed for energy examinations of the multisymptomatic high-cycle fatigue of the simple mechanical units' constructional materials".

1 INTRODUCTION

Within the period of intensive works engaged upon the improvement of reliability, durability and economy of marine combustion engines' action, a problem of the effective diagnostic methods gets the more and more larger meaning - especially, because last several years there was observed getting off the engines' planned maintenance operation instead of their operation according to the actual technical state (MAN Diesel&Turbo - „CoCoS-EDS - **Co**mputer **Co**ntrolled **S**urveillance - **E**ngine **D**iagnostic **S**ystem", Wärtsilä - „CBM - **C**ondition-**B**ased **M**aintenance", General Electric - „ICAS - **I**ntegrated **C**ondition **A**ssessment **S**ystem"). This is a desirable activity especially in case of the unforeseen damage inputs the large hazard degree. It also concerns fatigue damages within the engine's mechanical system and its driving line where possibilities of early recognizing the diagnostic symptoms are extremely limited because of the very little supervisory susceptibility.

Hence, despite hearing more and more often about implementation into operation system a so-called complex (defined in such a way with a decidedly excessive, exaggeratedly manner), multisymptom diagnostic systems of the marine engines they still involve the working spaces mainly or the fuel fed systems eventually. Furthermore, a key diagnostic problem concerning an evaluation of the fatigue state of the elements within the engine's mechanical system (and within the whole propulsion system) still remains unsolved. These elements being exposed to cyclic, changeable loads undergo fatigue failures (cracks) [Hebda and Wachal, 1999]. This kind of failure seems to be foreseeable which results from a clear interdependence between the failure formation's intensity and the engine's worktime. Additionally, a dispersion of the occurring failures is contained in the narrow time interval - Fig. 1. However numerous deviations from this rule occur. They result most often from the post technological lattice defects within the constructional material, and also, what happens more often, from the long-lasting usage of the ship's propulsion system in conditions of a stability loss within the mechanical system and consequently, the resonance vibrations [Cudny, 1976; Drganantchev, 2000; Korczewski and Rudnicki, 2012].

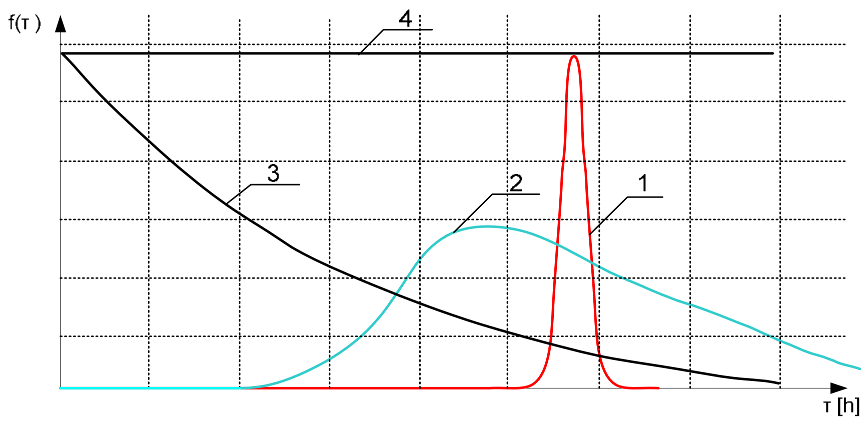

Figure 1: Hypothetical time courses of a probability density function of the worktime up to the failure for the marine combustion engines basic functional systems [Czajgucki, 1984].
1 – mechanical system, combustion chamber unit, 2 – thermal-flow systems, working spaces, 3 i 4 – control system.

Then, the occurring maximum amplitudes of changeable internal tensions cause a considerable limitation of the load alterations cycles' number, at which the elements transmitting a torque from the engine to the propeller undergo the accelerated fatigue wear and tear, up to the irreversible damages (cracks, deterioration of the constructional material's mechanical properties etc.) - Fig. 2. What is interesting, the fatigue state, in a sense of dislocations within the lattice, caused by amplitudes of the cyclically changeable tensions, is "memorized" by the constructional material and in spite of removal of the primary reasons extorting vibrations a spontaneous restoration of the primary mechanical properties does not follow. On the contrary, a fatigue weakening constructional structure becomes more sensitive to strenuous load alterations because the initial Wöhlera curve moves in the direction of more and more lower values of the transferred tensions as well as the smaller cycle number at which a fatigue cracks initiation follows, and so the smaller fatigue durability.

The operation experience within medium-speed combustion piston engines of the ship's main propulsion system proves, that camshafts of these engines represent equally vulnerable area. The engines' camshafts are exposed to, besides the above mentioned mechanism of the high-cycle fatigue, also tribology failures caused by top layer fatigue of the cams' tracks (pitting) - fig. 3. This is a result of the cyclic impact of thrust forces and simultaneous lube oil wedging's influence.

The problem of fatigue consequences of vibrations, as an energy "microdynamic" phenomena (quick-changeable), occurring within the material microstructure related to one cycle of the changeable load, has been represented in numerous publications within the range of the Materials' Strength for many years now [Kocańda and Szala, 1997; Kaleta, 1998; Boroński and Szala, 2008; Maciejewski et al., 2003]. However, there is still noticeable the

a) b)

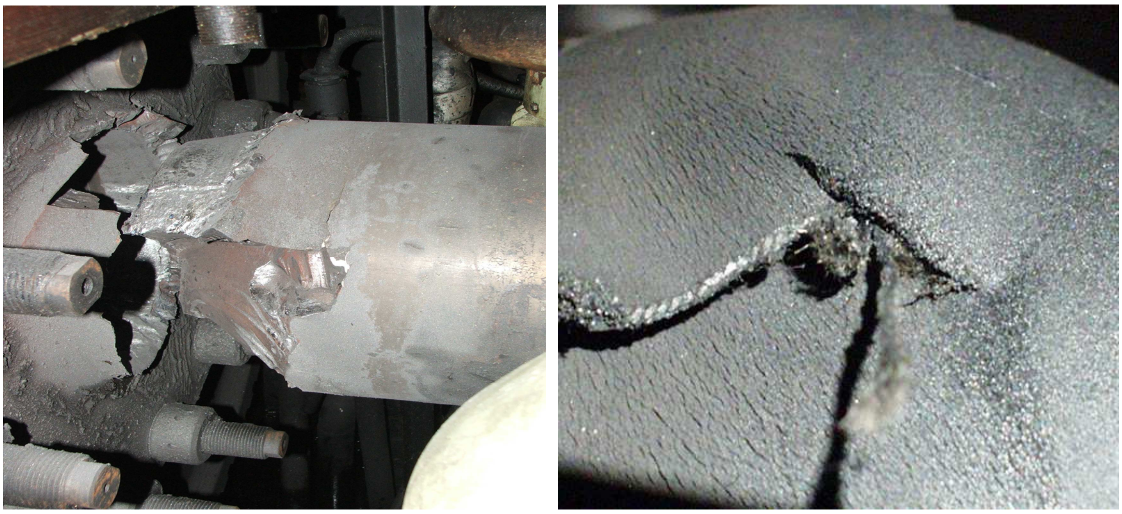

Figure. 2: Fatigue failures of the shaftings' elements within the marine propulsion unit:
a) broken propeller shaft of the marine propulsion unit as a consequence of the structural material's high-cycle fatigue (mechanical), b) rubber flexible element of the Vulkan RATO coupling along with fatigue wear traces.

a) b)

Figure. 3: Camshaft of the Sulzer-Wartsila marine four-stroke engine of 16ZV40/48 type:
a) cams's tracks worn by pitting - general view, b) the worn cam's working surface - magnification.

lack of bibliographic positions presenting this issue in an aspect of identification of the "macrodynamic" processes (slow-changeable), describing the material behavior in a macroscopic scale, during a continuous, transient flow of the mechanical energy flux (along with the energy's dissipation and accumulation) from the engine to the propeller.

In an ideal marine propulsion unit the whole energy delivered to the propulsion engine is transformed into the effective, basic rotational motion of the propulsive line's mechanical system. As the result of the progressive technical state degradation of the line's constructional elements accompanying motions are generated additionally. They are undesirable from the efficiency viewpoint of energy transformation and transmission processes within the whole propulsion unit. Moreover they represent a reason for the kinetic energy's dissipation of the masses within the rotational motion as well as the internal energy's accumulation within the constructional materials. After crossing the critical values of these energies the fatigue damage follows. Its course is characterized with residual energy processes: vibroacoustic and thermal that induce the observable diagnostic symptoms of technical state alterations.

Therefore, how to estimate quantitatively a current fatigue state of the constructional material of elements transmitting a torque within a simple mechanical unit of the marine propulsion system in operation condition? More and more perfect measuring apparatus unlocks completely new horizons in this regard. Its application in diagnostic investigations enables the user to observe precisely the course of residual energy processes within the mechanical unit. It aims to evaluate the measures' patterns (estimators) of diagnostic signals (vibration, acoustic and radiant emission) for the given high-cycle fatigue of the constructional elements' material. Consequently, this is also possible to evaluate a diagnostic inference method about the technical state of the simple mechanical units within the marine propulsion systems, and not only, in their operation conditions. This is the main aim which shone the Authors of the present article during planning the investigative project.

2 RESEARCH TEST STAND

In the first stage of diagnostic investigations of the real marine propulsion mechanical arrangements at high-cycle fatigue conditions it was necessary to build, in a certain scale, a physical model of the simplified mechanical system. The model preserving essential dynamic features of the real object enables an observation of the realized energy processes' course. There were good reasons for the decision to apply Schenck fatigue machine to this aim. The Schenck machine is mainly designed to evaluate the fatigue boundary of the constructional materials at the double-sided bending - Fig. 4. During the standard fatigue test a standardized sample of the constructional material is subject to the clear bending-torsion moment of the constant value, on its whole length. It means, that the same fatigue stress exists in its every section. In this way, by relating the conditions of the laboratory fatigue test to the real running conditions of the marine propulsion unit shafts misalignment or deflection might be simulated. Such undesirable malfunctions take the effect on the growing trust forces in bearings and therefore a growth of the mechanical losses moment for overcoming friction forces within the mechanical system takes place.

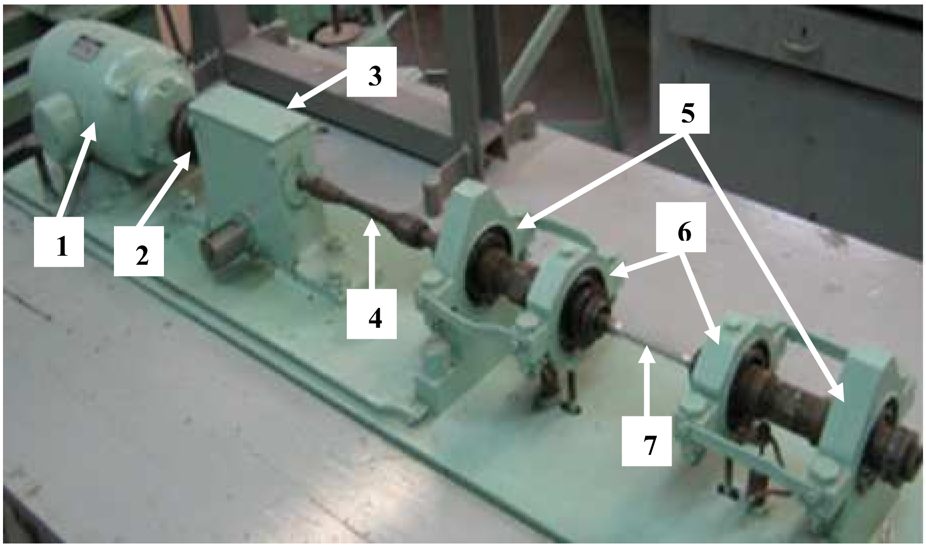

Figure 4: Standard Schenck fatigue-testing machine designed to exam a fatigue boundary of the constructional materials at the double-sided bending

1 – propulsion engine (shunt direct-current motor), 2 – silent-block flexible disk coupling (pins along with rubber pads), 3 – rev-counter worm gear (transmission ratio 1:100), 4 – spring-actuated flexible coupling, 5 – immovable rolling bearing (ball bearing), 6 – self-aligning rolling bearing (ball bearing), 7 – sample under investigation.

Because the alterations of the driveline's rotational speed represent an observable result of the unestablished balance of the system's mechanical energy and transverse vibrations generated in the bearing nodes, acoustic emission of disappearing springy waves as well as thermal emission (infra-red radiation) of the system's elements accumulating the internal energy stand for the additional consequences of the sample's enforced springy and plastic deformations the appropriate modernization of the existing, standard research test stand had to be carried out. In such a way simultaneous, the multisymptomatic, energy observation of the high-cycle fatigue process of the standard sample was able. A designed measurement system should make it possible a constant registration of the parameters characterizing different energy forms' accumulation and dissipation during a slow-changeable unsteady process accompanying the respectively planned fatigue test. The proposed solution of such a stand, which is presented in Fig. 5, has been protected by the Patent Office of the Republic of Poland, as a utility pattern, the registration number: 67362 - "Laboratory test bed for energy examinations of the multisymptomatic high-cycle fatigue of the simple mechanical units' constructional materials".

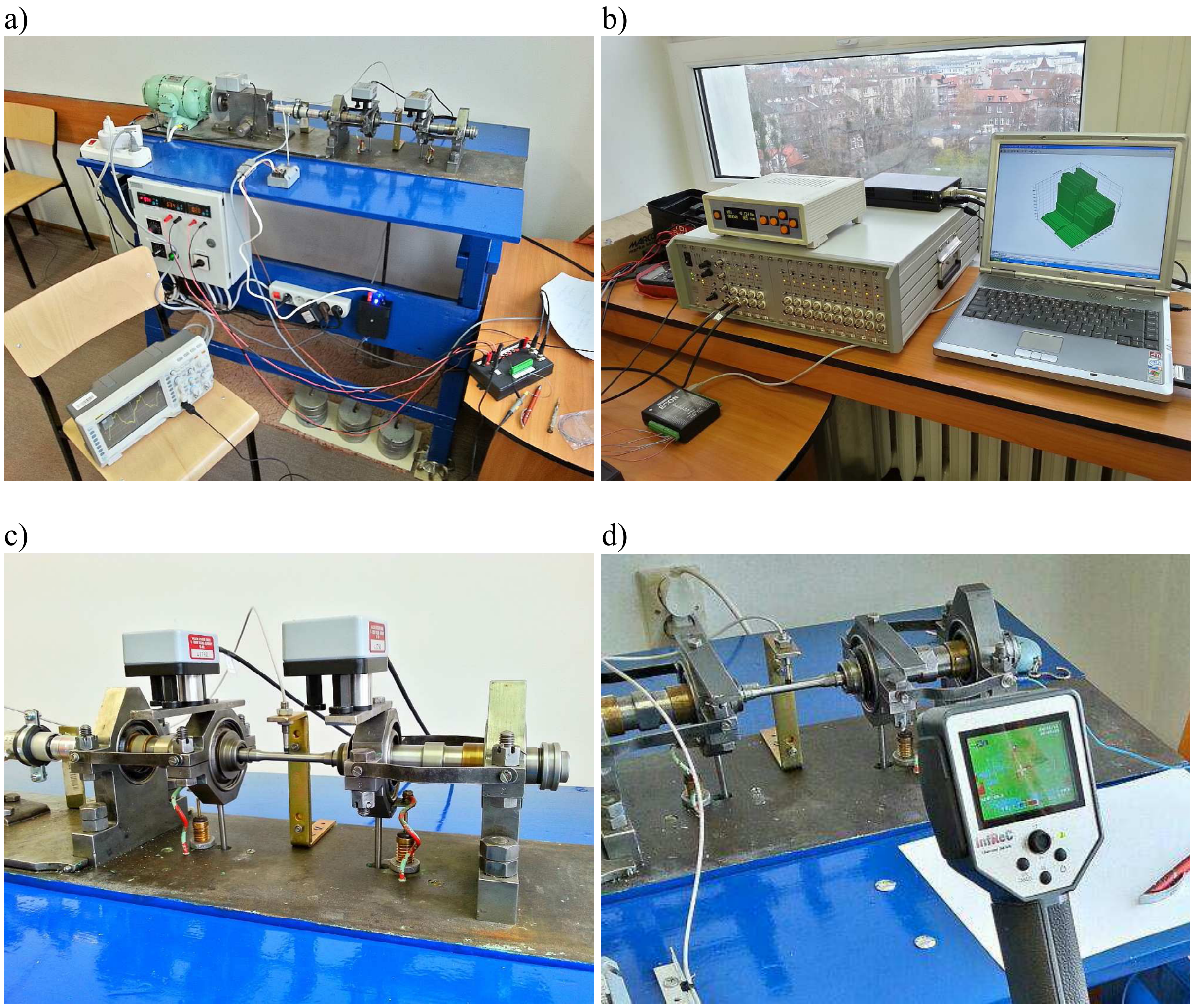

Figure 5: Modified Schenck fatigue-testing machine designed to energy examinations of multisymptomatic high-cycle fatigue of the rotational mechanical units:
a) general view, b) acoustic emission apparatus, c) torque, rotational speed, eccentricity (deflection), acoustic emission sensors, d) infra-red observation.

During a fatigue test completion there are registered diagnostic signals reflecting energy consequences of the progressive degradation process of the standard sample's structure material which is subject to rotatory bending. Within successive stages of the fatigue process: from an appearing the first slips in grains, across an initiation and development of the micro- and macro-cracks, until to the total fatigue destruction, the following physical quantities (signals) have been simultaneously recorded:

- shaft's rotational speed (electrooptical converter),
- shafts torque (torsion meter MT – 1Nm type, along with 2–channel register MW2014 type),
- sample's acoustic emission (Vallen Systeme GmbH register and analyser AMSY-5 type),
- sample's infra-red radiation (Nippon Avionics InfReC Thermo Gear G30 type),
- bearing nodes' vibration (Svantek vibration register and analyser SVAN956 type),
- sample's eccentricity (INTROL inductive approach sensor IGA005GU type),
- electric motor's current voltage and intensity (standard registers),
- consumed electric energy stream from the power network (Brennenstuhl register EM240DE3698 type).

They characterize quantitatively and qualitatively an energy state of the rotational mechanical unit. A flow of energy streams within of the considered mechanical system illustrates Fig. 6.

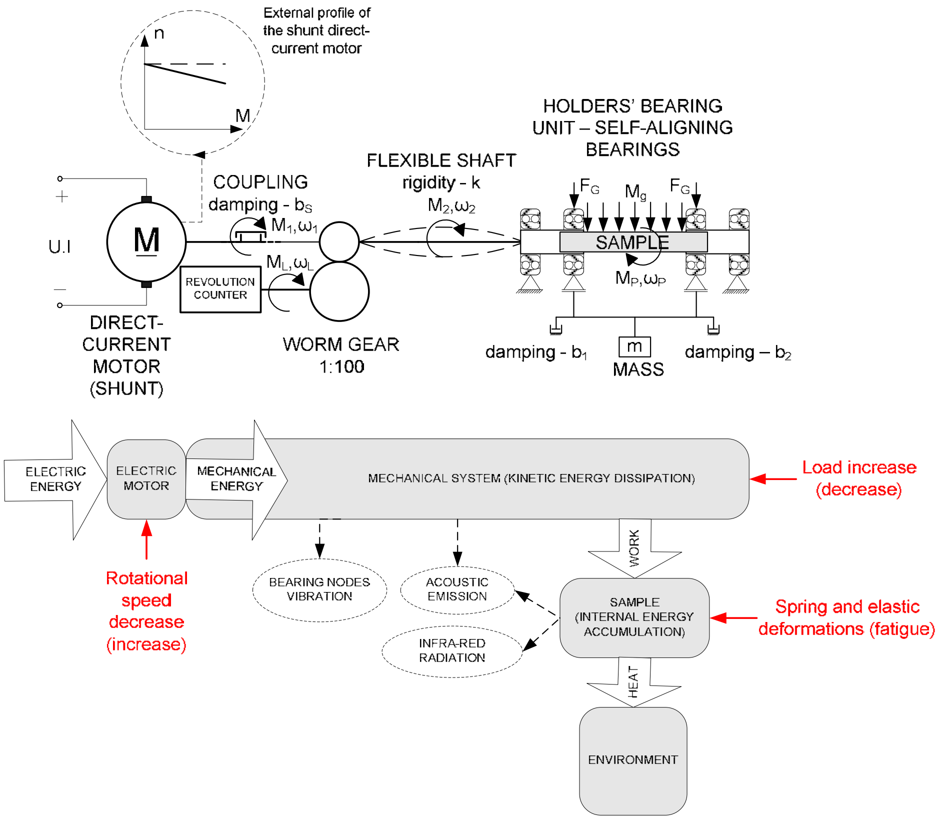

Figure 6: Mechanical system of the Schenck fatigue-testing machine along with a flow of energy streams

3 RESULTS OF THE PILOT EXPERIMENT

After starting-up the propulsion engine and getting-out the mechanical system from the standstill to the settled rotational speed 2000 rev/min the sample's loading with the bending moment follows. The sample's cyclic sinusoidal load induces cyclic fatigue deformations and stresses within the material structure. An initial growth and subsequent fall of the system's rotational speed represent, among the others, their observable diagnostic symptom. The rotational speed alterations stand for the measure of the appropriate alterations of the dynamic torque which characterizes the mechanical system’s ability to accumulate kinetic energy of the masses in rotatory motion - Fig. 7.

The initial growth and subsequent fall of the system's rotational might be explained with a response of the propulsion electric motor (shunt direct-current motor) to the stroke load’s growth and the transitional, equally intensive reinforcement of the sample's material structure in the result of slips' incubation in some grains of the lattice that are unfavorably-oriented in relation to the load direction. The material consolidates as a consequence of the plastic deformations extorting the evolution of the lattice's defects along with the mutual blocking dislocations that are moving in different, intersecting slips' planes. In the initial phase of this process trust forces in bearings as well as the propulsion engine's load torque will be the largest. There might be also observable maximal values of the sample's eccentricity (deflection) as well as the armature’s current intensity which gradually decrease up to minimal values.

With the next phases of the considered process the gradual weakness of the sample’s material follows. Only insignificant growth of the sample’s deflection and temperature takes place (therefore also a fall of the sample’s stiffness). The trust forces in bearings get smaller gradually which causes a gradual fall of the anti-torque in mechanical unit’s rotatory motion, that is to say the propulsion engine's load torque. According to the right of angular momentum alterations for the considered propulsion unit a kinetic energy accumulated in its mechanical system increases and an appropriate growth of the rotational speed is observed (stands for an observable symptom of the kinetic energy accumulation). In case of a shunt direct-current motor for the increased rotational speed, at unchanged magnetic stream, responds the largest counter-electromotive force which counteracts against the voltage. In such a situation the smaller current flows through the engine's armature getting smaller a turning moment generated in the engine. Considering this process in an aspect of electric energy transformation into mechanical one, what is worked out in the propulsion engine, it goes without saying that the smaller is the load torque the smaller is the current's amount consumed by the propulsion engine from the electric net (the smaller is an electric energy stream delivered to the engine). The slow changeable unsteady process will be lasted till the balance between breaking torque from the mechanical system (moment of the mechanical losses) and the engine's propulsion torque, unless the sample earlier undergoes a fatigue destruction.

An alteration of the temperature field in a deformed material as well as the permanent growth the sample's averaged temperature stands for the thermal consequence of the mechanical fatigue. Observable distribution temperature alterations on the sample's surface (learning on the infra-red radiation detection) represent, on a macroscopic level, the adequate diagnostic symptom of microscopic phenomena setting within the material's crystalline structure. The phenomena are mainly associated with the dislocations' movement as well as their interaction (an influence of the point defects is negligible small) [Boroński and Szala, 2008]. According to the first law of thermodynamics an alteration of the internal energy amount that is accumulated during the fatigue test realization is calculated as a sum of the heat flux emitted to surroundings and the power needed on the sample's material deformation handiwork. Taking into considerations energy hypotheses of the fatigue damages, presented in publications of scientific teams directed by S. Kocańda and J. Szala as well as J. Kaleta a constructional element undergoes the fatigue destruction, when a total internal energy accumulated in its material reaches the critical value [Kocańda and Szala, 1997; Kaleta, 1998].

A measurement and analysis of the vibration generated by the mechanical system's bearing nodes stands for the particularly complex metrological aspect of the high-cycle fatigue process's energy consequences in the conditions of growing lattice's defects of the material sample. This is also very complex to investigate impulses of disappearing springy waves of the acoustic emission that are locally freed, from the intermolecular bonds' energy release. What, in turn, is caused by the lattice's deformations and its defects' displacements (pointwise and linear). Then, the root-mean-square value (rms value) of the registered amplitude spectrum constitutes the basic diagnostic parameter, as a measure of dissipated kinetic energy of the mechanical system in rotational motion devoted to the vibration and acoustic emission enforcing. Within L. Rogera publications presenting the comparative analyses of both the methods in an aspect of the fatigue cracks identification of the rolling bearings you can find unequivocal conclusions confirming a decidedly larger efficiency of observation of the acoustic emission phenomenon, which is more tender and unambiguous in the material defects evaluation [Roger, 1979 and 2001].

Because of the continuous alterations of the lattice structure as well as temperatures of the getting warm material sample follow the suitable alterations of the natural vibration frequency follow. This frequency gets smaller along with the sample temperature, as a result of the material stiffness's decrease (a value of the material's longitudinal modulus of elasticity gets smaller). It results, from the conducted calculations, that in a range of the material temperature's changeability of the sample and bearing nodes, the natural vibration frequencies change in the range of a dozen or so, or even tens percentage during realization of the accelerated fatigue test. It can lead to the considerable "wander" of resonance frequencies. Hence, a frequency analysis of the registered amplitude spectrum does not bring in essential diagnostic information.

The representative time courses of the observed control parameters registered during the pilot fatigue test execution on the Schenck test stand were introduced in Fig. 7 and 8.

In the first considered case the propulsion system behaved naturally, because no physical quantity was stabilized. In the second case an assigned rotational speed was stabilized. A necessity of controlling the propulsion engine rotational speed as well as its stabilization within the wide range of alterations both the revolutions and the loads resulted from the experiment design. It was assumed that the created physical model of the rotational mechanical unit will behave like the majority of real propulsion systems' mechanical units, in which the automatic control system of the propulsion engine's load keeps up the rotational speed independently from the conditions alterations of the engine's load.

Such a function, within the marine propulsion systems powered by diesel engines, is fulfilled with a multi-range rotational speed governor that controls the propulsion engine's injection pump setting (a fuel charge).

A constant rotational speed maintenance of the propulsion engine (electric, direct-current motor), within the control system of the laboratory physical model, is worked out by means of appropriate changes of the current intensity flowing through the armature altering a torque generated in the engine.

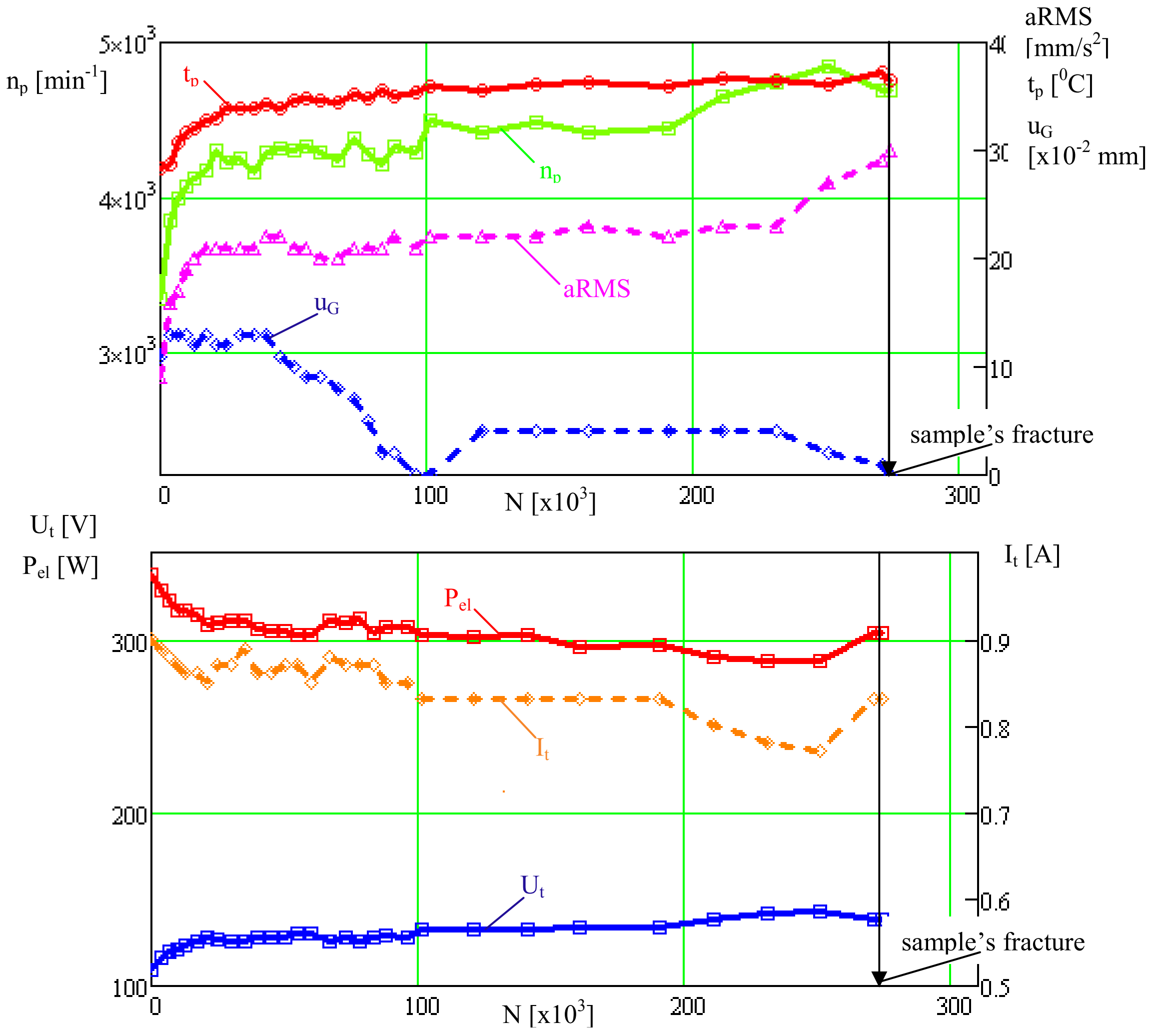

Figure 7: Time courses of the observed control parameters registered during the pilot fatigue test execution on the stainless-steel sample (unalloyed, fine-grained, weldable steel of S355N type) – system without the rotational speed stabilization

t_p – sample's temperature, n_p – sample's rotational speed, U_G – sample's deflection, a – vibration acceleration, aRMS –root-mean-square value of the vibration acceleration, I_t, U_t – respectively: armature's current intensity and voltage, P_{el} – power delivered from the electric network, N – cycle number.

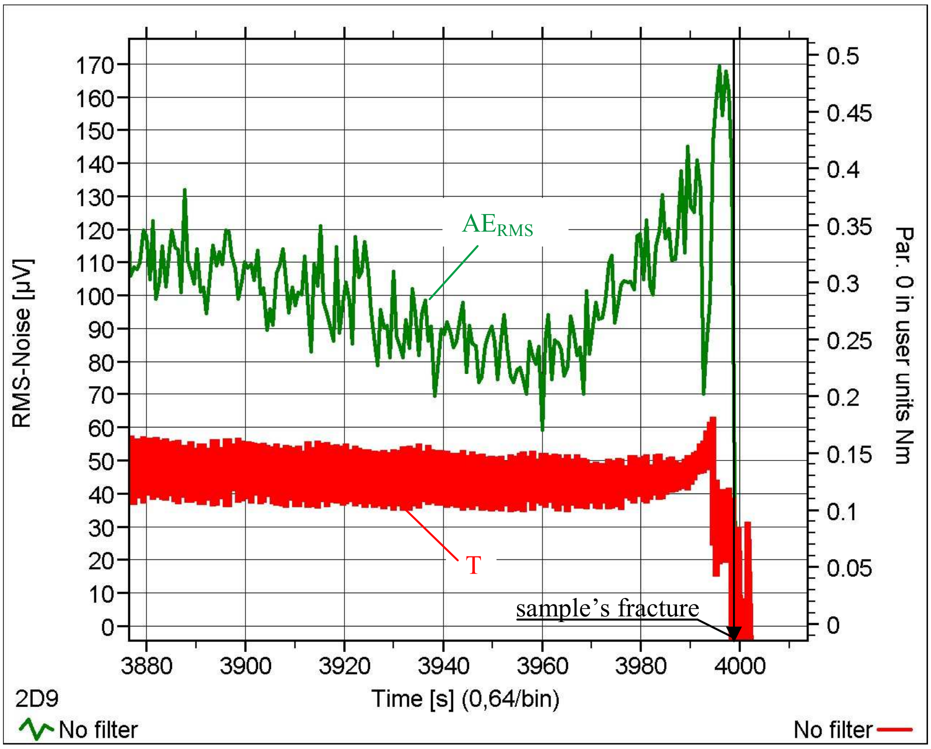

Figure 8: Time courses of the observed control parameters registered during the pilot fatigue test execution on the stainless-steel sample (unalloyed, fine-grained, weldable steel of S355N type) – system along with rotational speed stabilization at 2000rev/min
AE_{RMS} – root-mean-square value of the acoustic emission, T– torque.

4 CONCLUSIONS AND FINAL REMARKS

The conception introduced within this scientific study concerns a diagnostic application of the energy investigations of the slow-changeable unsteady processes that go with the high-cycle fatigue of materials and constructions of the simple, rotational mechanical systems. It represents an introduction to wider research works devoted diagnostic methods applicable for the marine propulsion systems' mechanical units in their real operating conditions. There is foreseen, that the elaborated method of the mechanical units' technical shape evaluation will supplement a lacking link of the existing diagnosing systems of the marine engines and propulsions.

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